Wake-up Radio Ranges: A Performance Study

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***Abstract*—Wake-up radio technology helps to attenuate unnecessary power consumption by allowing a node to keep its main radio off until it is *woken up* by a signal to an auxiliary low-power radio receiver. In this paper, we evaluate the range performance of an ultra-low power wake-up radio receiver (WuR) integrated into a wireless device suitable for wireless sensor networking deployments. We run several ranging experiments, both indoors and outdoors, where a transmitter sends wake-up sequences to a receiver positioned meters away. We measure the amount of received sequences and whether they incur errors or not. Our experiments show that for distances up to 24m indoors the tested WuR receives more than 96% of the transmitted sequences. The WuR performs slightly better outdoors, with more than 99% of the sequences being received with negligible amounts of errors.**

I. Introduction

A host of increasingly popular and important networking applications, including those for wireless sensor networks (WSNs) and for the Internet of Things (IoT), require large deployments of battery-powered devices networked to communicate wirelessly. Widespread usage of such applications is however beset by the network short operational lifetime. This is due to (i) the relative short life span of the batteries powering the network nodes; (ii) the scarce efficiency of small form factor energy harvesters (if any is available to the devices) [1], and (iii) the continuous drain of energy of a node that is sensing and/or computing and/or communicating, i.e., transmitting and receiving bits, but also being idle.

Energy-efficient solutions to the problem of prolonging network lifetime have been proposed at all level of a network node architecture, and at all level of the networking protocol stack. Efficient micro-processors, faster memories, low power radios, energy harvesters, are all examples of how hardware and software design can be aimed at improving the lifespan of a battery-powered device [2], [3], [4], [5].

One approach to decrease energy consumption is to have nodes operating according to set *duty cycles* [6], [7]. Nodes switch between a "dormant" state, where their radio (and possibly other circuitry) is turned off, and an "active" state, where they turn their radio on, allowing for communication. Energy is saved because while a node is dormant it consumes orders of magnitude less energy than when it is in active state. However, this comes at the cost of a significant increase in data delivery latency [8]. In fact, for many applications the latency induced by duty cycling is unacceptable.

A more recent approach to conserving energy is the use of *wake-up radio receivers* (WuRs) [9], [10]. Nodes use an auxiliary, ultra-low-power receiver that is listening to the communication channel for a wake-up signal (usually, a sequence of few bits). By default, the node remains in a dormant state, wherein its main radio is turned off. When a specific wake-up sequence is received by the WuR, the main radio is turned on, setting the node to its active state. The node manages its communications, and then returns to its dormant state. This strategy significantly reduces the power consumption of the network, without suffering the bloated latency of duty cycling [8]. Many works have been presented where the feasibility and advantages of using WuRs is demonstrated via simulations of networked systems in several different scenarios. (A selection of these works include [11], [12], [13], [14], where further references can be found.) However, a characterization of the performance and feasible ranges of ultra-low power WuRs has never been presented in details.

In this paper we aim at evaluating the performance of a WuR prototype integrated into a wireless device that is suitable for WSN and IoT deployments. Particularly, we set out to evaluate the wake-up ranges attainable by a WuR designed to have high sensitivity, fast reactivity, very low power consumption, and selective addressing capability. The latest design of the selected WuR prototype, presented by Magno and Benini [15] and by Spenza et al. [14], is described in details in Section II, along with its integration into a wireless mote. We tested two different versions of the receiver, each optimized to work on a different frequency, namely, 868 MHz and 433 MHz. Experiments were run both in indoor and outdoor locations. We observe that the tested WuR receives more than 96% of the transmitted sequences, on both frequencies and in an indoor scenario for ranges up to 24 meters. The performance on the 868 MHz frequency results to be slightly better than when operating at 433 MHz, with a lower number of sequences received with errors. For both frequencies, the prototype performs slightly better outdoors, with more than 99% of the sequences being received and with negligible amounts of sequences received with errors, up to 21 meters.

The remainder of the paper is organized as follows. Section II describes the WuR and its integration into a wireless mote. Section III details the experimental setup, the investigated performance metrics and presents the results of the experiments. In Section IV related works concerning wake-up radios are discussed. Finally, Section V concludes this work.

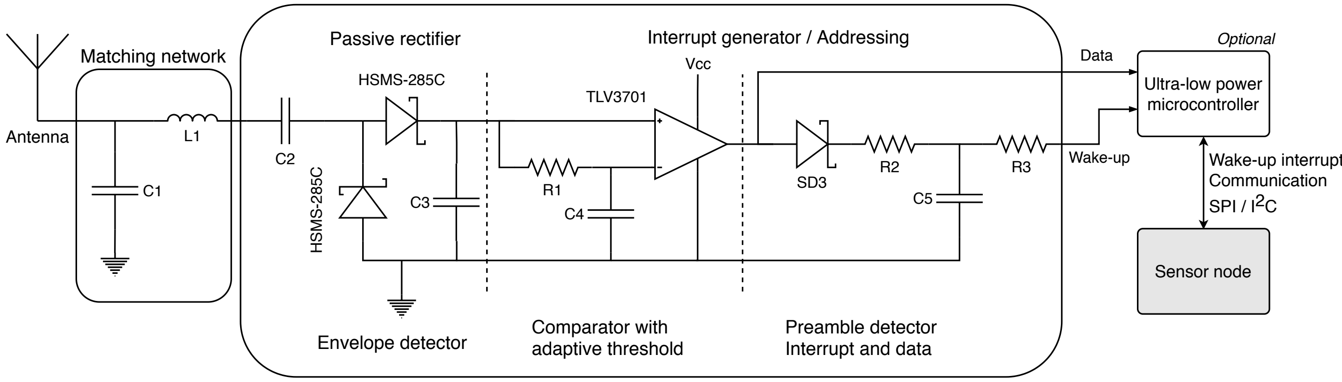


Fig. 1. Architecture of the wake-up receiver [14].

II. Wake-Up Radio Receiver and Integration

A. Wake-up radio receiver

The architecture of the WuR used in this work is depicted in Fig. 1 [14]. In this section we summarize its main components.

The receiver uses the On-Off Keying (OOK) modulation, one of the simplest forms of amplitude-shift keying modulation. Digital data are represented as the presence or absence of a carrier wave.

The first component is the *matching network*: it maximizes the power transfer from the antenna to the rest of the circuit. It consists of an LC filter, whose components are set based on the transmission frequency. In this work, we tested two different prototypes of the WuR, optimized to work either in the 868MHz frequency or in the 433MHz frequency.

The output of the matching network is an RF signal from which information (i.e., the wake-up sequence) can be recovered. This task is carried out by the next two components. The *passive envelope detector* discards the frequency and phase content of the modulated waveform and only detects its amplitude, consistent with using OOK modulation. In the tested prototypes it consists of a single-stage half-wave rectifier with series diodes. In particular, the HSMS-285C diodes from Avago Technologies were used. They are optimized for sub-GHz frequencies and for incoming power levels lower than -20dBm. They achieve a sensitivity of -57dBm.

Once the signal is rectified, the bits of the received wake-up sequence are reconstructed by using an *ultra-low power comparator*. In order to reduce the static power consumption of the circuit, an adaptive threshold mechanism keeps the V^{-} pin of the comparator at half of the input signal level. This allows to avoid the use of a voltage divider, as the threshold is generated using the energy coming from the antenna. The choice of the comparator influences the power consumption of the WuR, because it is the only active component of the design, as well as its overall sensitivity. In fact, comparators with a lower voltage offset are able to sense smaller signals. However, such comparators typically have higher current consumption. The considered prototypes feature the TLV3701 comparator from Texas Instruments, which has a reasonable current consumption of 560nA.

The last component of the WuR is the *preamble detector*. It is used to filter out interference due to noise or other communications that can trigger unwanted awakenings. For this purpose, a preamble is added at the beginning of the wake-up sequence. The preamble is an OOK modulated signal representing a specific sequence of bits that is sent at a specific bit rate f_p. On-off keyed modulated signals that are sent at a data rate lower than f_p are discarded by the RC section of the preamble detector, which works as a low-pass filter. If a preamble is received at the f_p bit rate, the preamble detector generates a wake-up interrupt to either the sensor node's MCU or to an optional on-board ultra-low power micro-controller that reads data directly from the output of the comparator and performs address matching.

The optional ultra-low power micro-controller (e.g., the PIC12LF1552 from Microchip [16]) relieves the sensor node of the wake-up address recognition task and allows it to remain in the sleep state until a valid address is received. Hence, it decreases the total energy consumption.

This design obtains desirable characteristics for a WuR, namely, very low power consumption (< 1.3 μW) and high sensitivity (up to -55 dBm).

B. System integration

We tested the two versions of the WuR by integrating them into a wireless mote designed for WSN applications, namely, the MagoNode++ [17]. Fig. 2 shows a snapshot of a MagoNode++ featuring the WuR prototype on top of the casing used in our experiments.

The MagoNode++ is a low-power wireless mote equipped with a microcontroller/transceiver bundle. The microcontroller is based on a 8-bit, 16MHz CPU featuring 256 KB of ROM and 32 KB of RAM. The integrated transceiver is a 2.4GHz, 802.15.4 compliant radio module connected to a radio front-end that gives higher radio performance with low-power consumption. The wake-up extension board designed for the MagoNode++ is made up of two main components: The wake-up transmitter and the WuR. As mentioned, these components differ depending on the wake-up frequency used, namely, 868MHz or 433MHz. The wake-up transmitter is based on the CC1101 transceiver from Texas Instruments, a low-power

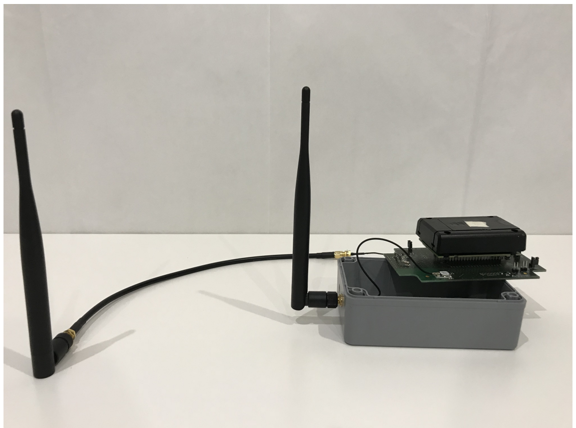


Fig. 2. A MagoNode++ mote with a WuR.

Fig. 3. Indoor setting.

sub-1GHz transceiver that supports OOK modulation [18]. The wake-up receiver is the one described in Section II-A. Wake-up transmitter and receiver use two separate antennas with a 50Ω impedance and gain depending on the frequency. The two wake-up antennas are connected to the wake-up transmitter and to the WuR circuitry. In order to avoid any distortion of the emitted electromagnetic fields, in our experiments we keep these two antennas at a distance δ higher than the near-field distance, which depends on the frequency and on the size of the antenna. The impedance matching of the RF section was carefully designed to provide the maximum power transfer between the antenna and the rest of the circuit. Details on the tuning of the matching network have been presented in [15]. The designers also chose to use separate antennas for the wake-up system and the main radio (which is integrated in the MagoNode board) for greater accuracy in assessing the performance of the WuR. Wake-up signals generated by the WuR are sent to the MagoNode++ through a low-level asynchronous interrupt pin of the microcontroller. Asynchronous interrupts are able to wake-up the MagoNode++ from the dormant state, in contrast with synchronous interrupts that can be triggered only when the node is in idle mode.

III. Performance evaluation

A. Scenarios and settings

In our experiments we used the MagoNode++ mote with WuR capabilities described in Section II. We tested WuR prototypes operating at 868 MHz and at 433 MHz.

We measure WuR range performance by placing a sender node S and a receiver node R at a given distance d, with d varying in $\{3, 6, 9, \dots, 24\}$ meters. We consider both indoor and outdoor settings, all located within the premises of the Computer Science department of the University of Rome "La Sapienza," Italy. Our indoor experiments were performed in a corridor of the building (Fig. 3). The outdoor space is the building courtyard.

Sender and receiver exchange wake-up sequences each 8 bits long. Because of hardware constraints, the sequences contain no six 1 in a row. This results in 248 *viable sequences* that can be received by the WuR.

Each sequence is preceded by a 4-bit preamble to allow the WuR to signal the wake-up interrupt needed to start the address matching phase.

The transmission power of the wake-up sequences is set to 10dBm.

B. Investigated metrics

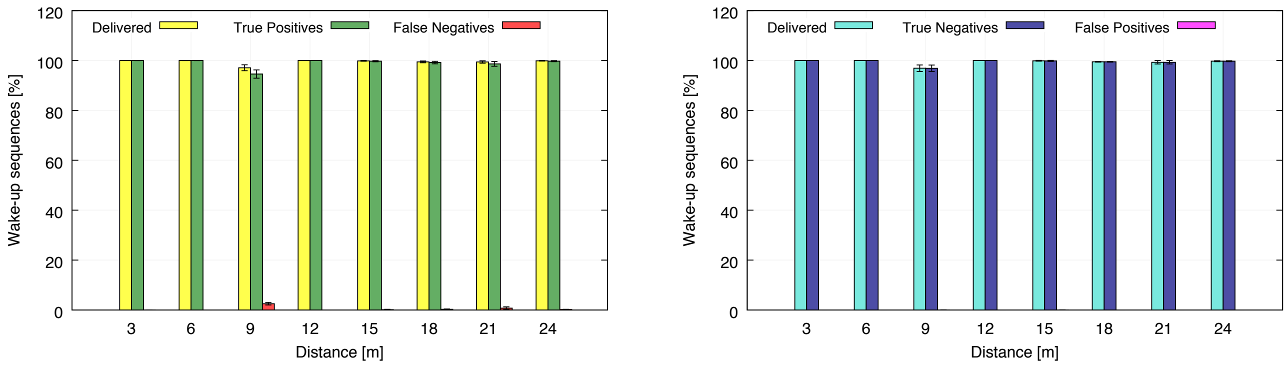
We selected 50 among all viable sequences. Each selected sequence s is set as the wake-up sequence of node R. Node S then sends sequence s to node R. This is repeated 25 times in total, with each copy being sent every 100 ms. For each sequence, we measure the following:

1) *Sequences delivered*: The percentage of sequences received by node R.
2) *True positives*: The percentage of sequences received correctly (node R would correctly wake-up).
3) *False negatives*: The percentage of sequences received incorrectly (node R would not wake-up while it should).

Sequence s is then transformed into a sequence s' by flipping one of its bits, chosen randomly. If s' is not a viable sequence (i.e., it contains six 1 in a row) it is discarded, and a new sequence s' is created. If s' is viable, node S sends sequence s' to node R. This is repeated 25 times, with one transmission every 100 ms. For each flipped sequence, we measure the following:

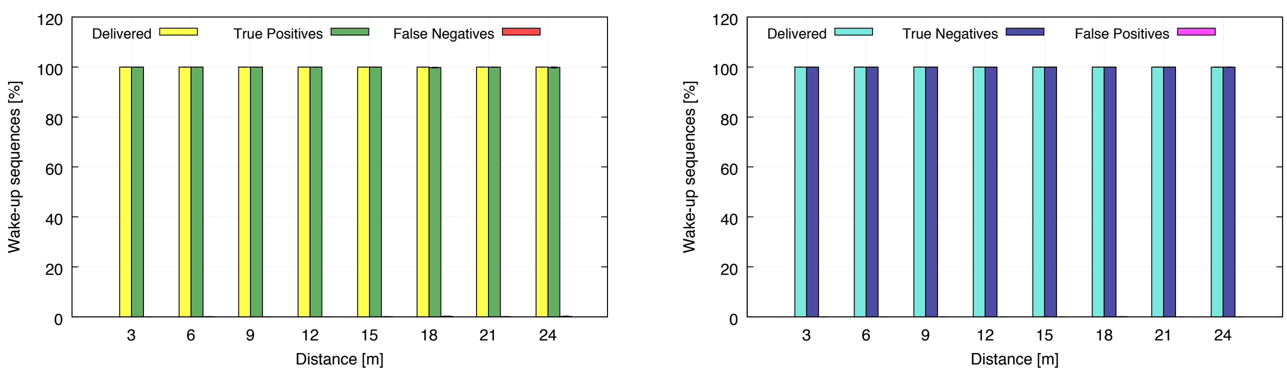
1) *Flipped sequences delivered*: The percentage of sequences s' received by node R.
2) *True negatives*: The percentage of sequences s' that have been received different from sequence s (node R would correctly stay asleep).
3) *False positives*: The percentage of sequences s' that have been received incorrectly as sequence s (node R would wake-up while it should not).

The results show the average of the outcomes of 5 repetitions of the experiment at each distance d.



(a) (b)

Fig. 4. Indoor scenario, 868 MHz. (a): Viable sequences. (b): Flipped sequences.



(a) (b)

Fig. 5. Outdoor scenario, 868 MHz. (a): Viable sequences. (b): Flipped sequences.

C. Performance results

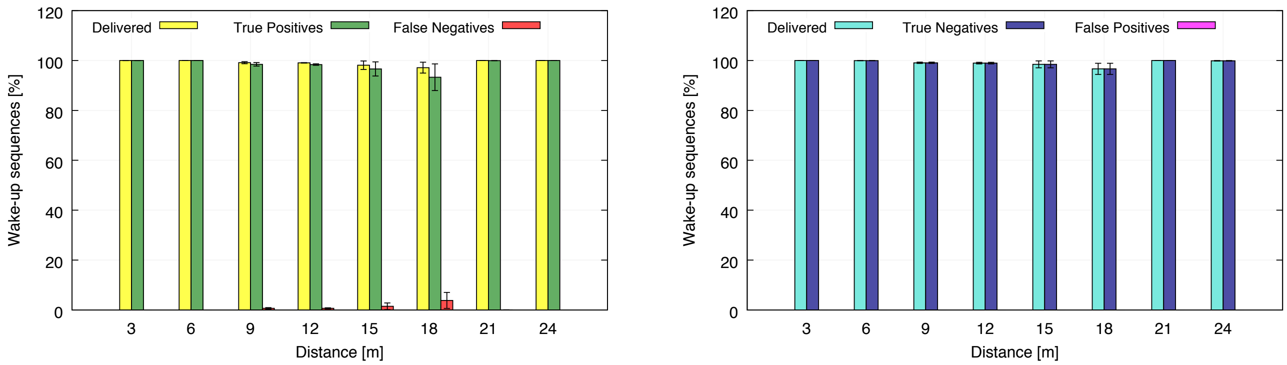
1) 868MHz: Results of indoor experiments are shown in Fig. 4a and Fig. 4b for viable and flipped sequences, respectively. The percentage of delivered sequences is above 96% over all the distances. False Negatives are consistently under 1% except when the distance between sender and receiver is 9 m. In this case 2.5% of the sequences incur errors. False Positives are negligible. Results of outdoor experiments are shown in Fig. 5a and Fig. 5b for viable and flipped sequences, respectively. At least 99.97% of the sent sequences were delivered to the receiver. These sequences were almost always correctly detected, since False Negatives are consistently under 0.2%. The only False Positives have been observed at 18 m in an insignificant amount (0.02%).

2) 433MHz: Results of indoor experiments are shown in Fig. 6a and Fig. 6b for viable and flipped sequences, respectively. The percentage of delivered sequences is above 96% over all the distances. At 15 and 18 meters there is a small amount of False Negatives, i.e., of viable sequences received with some errors: 1.48% and 3.84%, respectively. At the same distances there is also a significant increase in the variance of the results. Results of the outdoor experiments are shown in Fig. 7a and Fig. 7b for viable and flipped sequences, respectively. At least 99.92% of the transmitted sequences were delivered to the receiver. The viable sequences were almost always correctly detected up to 21 meters (a negligible amount of False Negatives has been observed at 15 and 18 meters). At 24 meters the performance begins to degrade, as 13% of the sequences incurs errors. During both indoor and outdoor experiments no False Positives have been received.

In general, for practical purposes both prototypes work well up to 21 meters. This provides us with a distance that can be safely used in larger testbeds and in simulation models. The slightly worse results in the indoor scenario are to be ascribed to the multi-path effect induced by the narrow corridor.

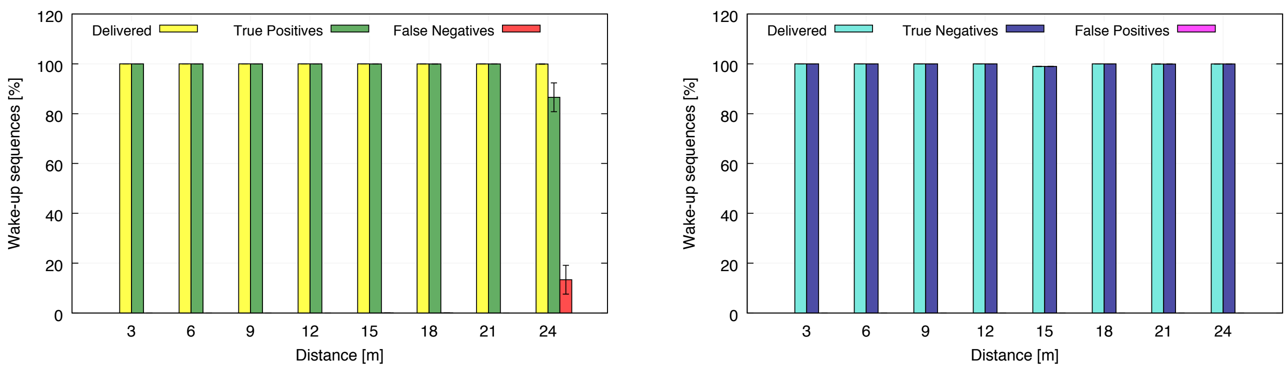
IV. Related Works

Research on WuR technology has been steadily increasing for over a decade. The various facets of the design space of WuRs have been surveyed, identifying key points of interest for study [9]. Recent years have seen the advent of novel WuR approaches and implementations [10], [15]. Many approaches to WuR feature low-frequency or low-bandwidth solutions, as protocols need to rapidly reawaken sleeping nodes. Such planning has led to the development of various applications and



(a) (b)

Fig. 6. Indoor scenario, 433 MHz. (a): Viable sequences. (b): Flipped sequences.



(a) (b)

Fig. 7. Outdoor scenario, 433 MHz. (a): Viable sequences. (b): Flipped sequences.

protocols that specifically cater to WuR implementations [11], [12], [13].

There have been numerous other studies about the radio characteristics of WuR nodes. Many of them propose new types of WuR technology [19], [20], [21], [22]. Other studies are more analytic in nature. For example, Nilsson and Svensson [23] propose a theory for evaluating envelope detector (ED) sensitivity. This theory is experimentally verified, and the sensitivity of the ED is analyzed. Moazzeni et al. [24] examine the power-sensitivity trade-off in tuned radio frequency receivers. Ramos-Valido et al. [25] examine the characteristics of multiple WuRs across different architectures and topologies. Finally, studies such as Mazloum and Edfors [26] comprehensively examine the influence of WuR characteristics on WSN energy consumption. To the best of our knowledge, no realized prototypes have been tested for range performance.

V. Conclusions

In this paper we have evaluated the range performance of a wake-up radio receiver designed to have high sensitivity and very low power consumption. We tested two versions of the WuR integrated to work with MagoNode++ motes. The tested prototypes are optimized to work at two frequencies: 868 MHz and 433 MHz. We sent a pool of 8-bit wake-up sequences between two motes placed at increasing distances and determined how many of them were received and whether they were received with errors or not. We then intentionally flipped one bit of every sequence in the pool and repeated the experiment to see if potential interference could alter the transmitted sequence and produce a False Positive. The experiments were run at both indoor and outdoor locations. We found that the tested WuR can receive more than 96% of the transmitted sequences, on both frequencies, indoor. On the 868 MHz frequency we observed that less sequences are received with errors. Both the receivers perform better outdoors, with more than 99% of the sequences being received at distances up to 21 meters. False Positives were rare across all experiments.

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